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INTERVENTIONAL IMAGING: THE ROLE OF ECHOCARDIOGRAPHY

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Abstract

Interventional echocardiography is a rapidly evolving field requiring imaging expertise. An increasing number of structural heart interventions now require real-time imaging guidance for device placement and immediate functional evaluation. Continuous 2- and 3-dimensional transesophageal echocardiography are now required by many heart teams during complex structural interventions, including percutaneous closure of atrial septal defects, left atrial appendage occlusion, transcatheter aortic valve replacement (TAVR), transcatheter repair of paravalvular regurgitation, and percutaneous mitral valve repair. In this review, we describe the role of echocardiography during the initial structural evaluation, throughout the device placement procedure, and for the assessment of acute device function and complications.

Introduction

Interventional imaging is an emerging field of expertise within the broader scope of functional cardiac imaging. Its development has been mandated by rapid advances in multiple percutaneous technologies to address a variety of structural heart pathologies. In general, transesophageal echocardiography is the primary imaging technology employed by the echocardiographer or anesthesiologist to assist with these procedures. Transesophageal echocardiography has a role in the initial assessment of the structural defect, monitoring of the intracardiac access and deployment of the device, the acute assessment of device function, and monitoring for any procedural complications. In this brief review, we discuss the established and emerging role of 2-dimensional and 3-dimensional transesophageal echocardiography during structural heart interventions.

Percutaneous Closure of Atrial Septal Defects

Percutaneous closure of a patent foramen ovale (PFO) has been shown to be a safe procedure, and various types of implants from different vendors have been available in clinical practice during the past two decades.[1-3] Although the efficacy of PFO closure for primary stroke prevention therapy remains controversial, it is considered reasonable for patients with PFO and high-risk features for venous thrombosis and/or recurrent stroke despite optimal medical therapy. Complications are rare with this procedure, and the Amplatzer™ PFO occluder (St. Jude Medical, Inc., St. Paul, MN) has been shown to be safe in the RESPECT and PC trials.[1-3] Rare complications include device thrombosis, atrial fibrillation, air embolization, and device embolization. Percutaneous closure of secundum atrial septal defect (ASD) has also been used widely in clinical practice, especially in cases with severe right-to-left shunt.

The accurate assessment of ASD or PFO anatomy is critical for successful device closure. As such, the echocardiographer must localize the defect, accurately assess the defect size and shunt severity, and characterize the number and complexity of septal defects (Figure 1).[4] In PFO closure, tunnel length and any associated septal aneurysm are important factors to be described.

Transesophageal echocardiography (TEE) may also identify common associated lesions such as cleft mitral valve and partial anomalous pulmonary vein drainage. According to current guidelines,[5] traditional midesophageal 4-chamber, midesophageal short axis, and midesophageal bicaval are commonly recommended to appreciate the entire ASD geometry. It is particularly important to characterize the tissue rims bordering the ASD. By convention, the rims are named for the adjacent structures, such as the superior vena cava rim, the posterior rim, the aortic rim, the coronary sinus rim, and the inferior vena cava rim. In general, the absence of an aortic rim is not a contraindication for device closure but will require over-sizing of the occluder.

An advantage of 3-dimensional (3D) TEE over conventional 2-dimensional (2D) TEE is its ability to demonstrate the dynamic morphology of complex ASDs, including an accurate depiction of asymmetric geometries such as elliptical or fenestrated septal defects.

In one study of 24 patients with complex ASD, use of 3D TEE compared to 2D TEE alone was shown to result in less residual shunt, presumably due to a more accurate assessment of the size and shape of the defect.[6] In addition, 3D TEE has added value in identifying patients who are at greater risk of erosion due to contact of the occluder device with the aorta.[7] Another advantage of 3D TEE is the ability to see en face views from both the atria. This may help visualize the defect before the procedure, identify multiple fenestrations, and assess the device deployment position postprocedure (Figure 2). Use of the 3D "zoom mode" is often employed to easily appreciate the location of guide wires, sheaths, and devices in real time.

Left Atrial Appendage Occlusion

Left atrial appendage (LAA) closure devices have been proposed as an alternative treatment option for patients with nonvalvular atrial fibrillation who are not eligible for

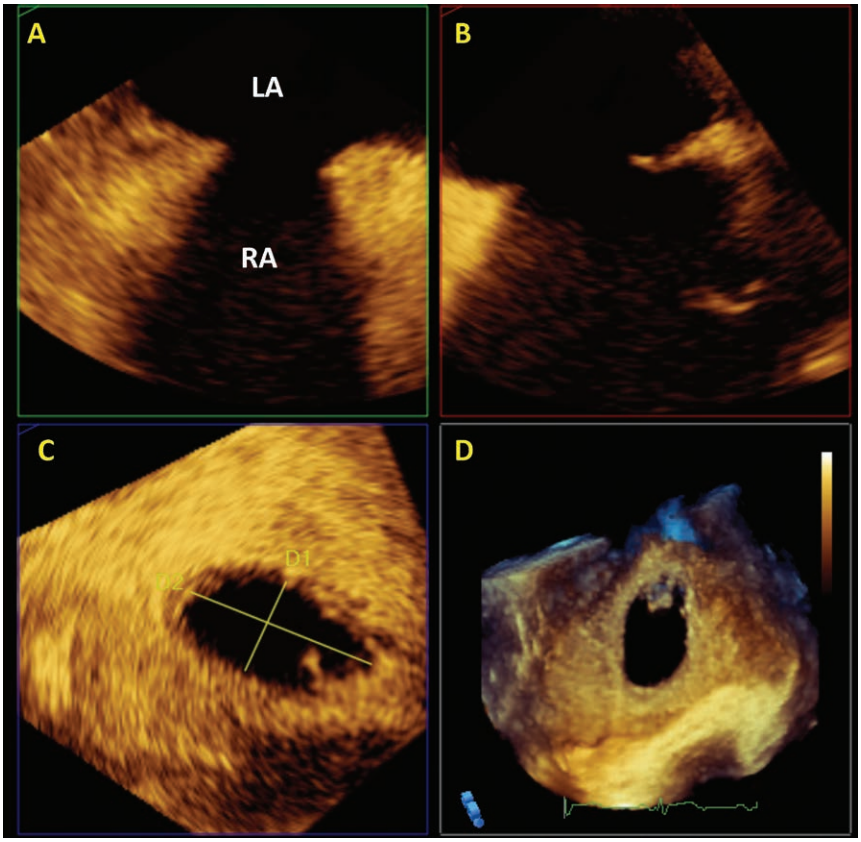

Figure 1. Sizing a secundum atrial septal defect (ASD) by 3-dimensional transesophageal echocardiography (3D TEE). (A-B) Simultaneous long axis views to define the ASD dimensions and geometry. (C) Short axis view of the ASD showing minor (1.2 cm) and major (2.3 cm) diameter of the defect. (D) 3D volume rendered image of the defect as viewed from the left atrium.

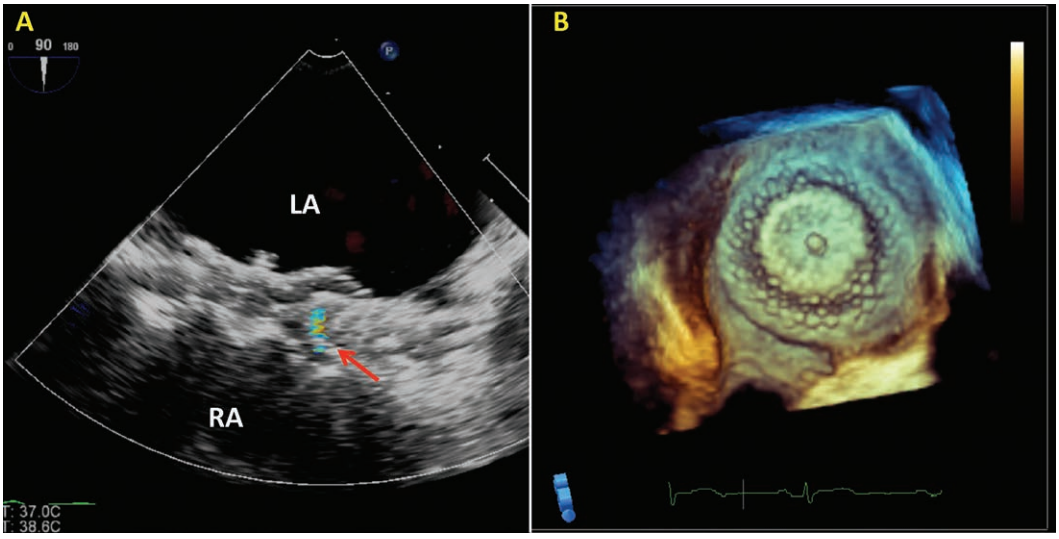

Figure 2. Functional assessment of atrial septal defect (ASD) closure device. (A) A well-seated device (Amplatzer™ ASD occluder) with small residual shunt detected by color Doppler noted immediately after deployment (red arrow). (B) 3D volume rendered image of the occluder as viewed from the left atrium.

anticoagulation or are at high risk of bleeding. Although percutaneous closure devices have been available for a decade, there is only one randomized trial (PROTECT AF) that demonstrates the benefit and safety of the transcatheter LAA occluder. This study showed non-inferiority of the device when compared with the oral anticoagulation arm for the primary endpoint of stroke, emboli, or death.[8] While the PLAATO device (PLAATO System, ev3 Inc., Plymouth, MN) had been used in the past for LAA occlusion, the most widespread devices in current use are the Watchman device (Boston Scientific, Natick, MA) and the Amplatzer™ Cardiac Plug (St Jude Medical, Inc., St. Paul, MN). There is also the LARIAT device (SentreHEART, Inc., Palo Alto, CA), a magnet-tipped catheter with a pre-tied suture that is guided within the pericardial space to encircle and seal the LAA.

TEE is the current modality used to guide devices involving transcatheter LAA occlusion procedures. A standard view to image the LAA is the midesophageal (ME) LAA view at 0°, 45°, 90°, and 135°; however, the LAA can be nicely depicted in other views. TEE is also useful in defining the variable anatomy and excluding thrombus before the procedure. The accurate LAA ostium diameter assessment plays an important role in selecting the appropriate device size. TEE may guide the proper transseptal puncture and verify the ideal positioning of the device before final deployment, and color Doppler may identify leaks even before device release. Postimplantation, TEE can ascertain the success of the procedure and investigate for possible complications. Routinely, TEE will assess the pulmonary vein flow and proper implant positioning and investigate for leaks and thrombus formation.

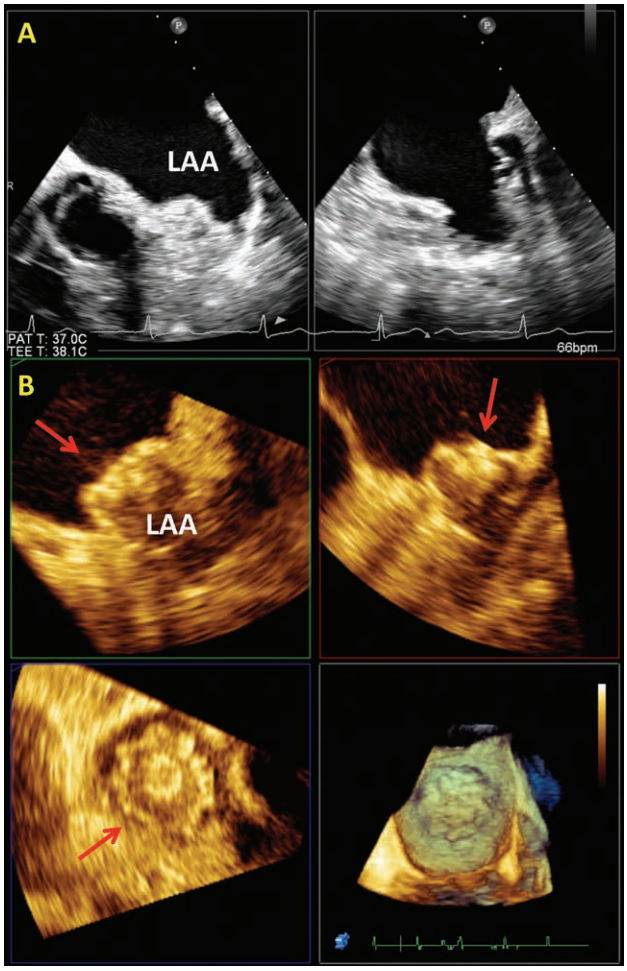

Figure 3. Left atrial appendage (LAA) occluder placement. (A) Biplane view of LAA showing two simultaneous orthogonal views prior to device deployment. (B) 3D acquisition of a well seated Watchman occluder device (red arrow) in two orthogonal views (above) and short axis views (below).

Recent guidelines[5] note that the LAA can be adequately assessed by 3D echocardiography. 3D echocardiography studies have clearly shown LAA oval shape with more than one lobe in many cases and has proven superior to 2D TEE in measuring LAA orifice size.[9] It also has been successfully used to guide catheter advancement and device implantation and to evaluate the function of the implanted device after the procedure (Figure 3).[10]

Although a high implantation success rate has been shown with the Watchman device, a peridevice leak rate of 32% has been reported at 12 months.[11] Serious complications have been reported in the PROTECT AF trial, including large pericardial effusions, major bleedings, device embolization, and periprocedural strokes. Either 2D or 3D TEE is the modality of choice to identify these structural complications.

Transcatheter Aortic Valve Replacement (TAVR)

Transcatheter valve replacement has evolved substantially since the first implantation in 2002.[12] Various vendors have developed different valve designs, such as the CoreValve (Medtronic, Inc., Minneapolis, MN), the SAPIEN valve (Edwards Lifesciences, Irvine, CA), and the Portico™ valve (St. Jude Medical, St. Paul, MN). Different routes have been applied for valve delivery and implantation, such as transfemoral, transapical, and subclavian. Patients with severe symptomatic aortic stenosis who are at high or prohibitive risk for surgical valve replacement are eligible for the TAVR procedure.

During TEE, a 120- to 130-degree midesophageal long axis view has routinely been used to size the annulus before the procedure. The diameter of the sinus of Valsalva, sinotubular junction, and ascending aorta are also measured. Although TEE was the initial method to assess annular diameter and to select prosthetic valve size, increasingly this role is being performed by multidetector computerized tomography (CT) prior to the procedure. This migration to CT imaging is largely in response to the recognition that the aortic annulus is usually noncircular and that a single 2D diameter measure using 2D TEE may underestimate the true annular area. In contrast, 3D TEE can be used to provide accurate assessment of even noncircular annular dimension, albeit with more effort than is typically required of CT data interpretation.

During the procedure, TEE ensures proper monitoring for the ideal valve deployment depth, which may differ among patients and among different manufacturer devices. A midesophageal short axis view (ME SAX, 25° to 45°) may help visualize the degree of calcification preoperatively and the catheter position at the cusps level during the procedure. Deep transgastric (0° to 20°) and transgastric long axis views (120° to 140°) are used to image the prosthetic aortic valve after implantation. Color Doppler may reveal aortic regurgitation preoperatively and assess prosthetic valve regurgitation after implantation. Continuous wave (CW) Doppler can be used to measure transvalvular gradients from the transgastric views; however, it may still be a challenge to obtain optimal alignment of the Doppler beam across the left ventricular (LV) outflow tract and new prosthetic valve.

Serious complications have been described during TAVR procedures, including obstruction of the coronaries, embolization of the device, significant mitral regurgitation, annulus rupture, and cardiac tamponade (Figure 4). However, the most common functional complication after valve implantation is paravalvular aortic regurgitation (PVR). While varying degrees of paravalvular leak have been reported in recent trials, it has been shown that patient outcome is adversely affected by any significant degree of PVR.[13]

The evaluation of eccentric paravalvular color Doppler jets can be extremely challenging. Entrainment of flow along the LV wall may cause misleading conclusions about the severity of the regurgitation.[14] Acoustic attenuation by the valve stent may mask significant regurgitation, and multiple sites of PVR may be present. Current guidelines recommend the 120-degree midesophageal long axis view or the 60-degree midesophageal short axis view for 3D image acquisition of the aortic valve. 3D TEE has been proven to have a better agreement when compared with CT measurements of the annulus size.[15] During the procedure, 3D TEE may adequately visualize the valvuloplasty balloon, the catheters, and the valve, and with the biplane view it is especially helpful in localizing the pig-tail catheter within the aortic sinus prior to any valve intervention. In this way, TEE is used to ensure that the landmark catheter for the interventionalist is actually at the lowest position within the aortic root, i.e., within the noncoronary cusp. 3D color Doppler may be used in addition to multiple-beat acquisition post procedure to evaluate the degree of paravalvular leak. Although there are no current guidelines defining the role of 3D echocardiography for accurate quantification of PVR in the TAVR population, recommendations on the use of echo during TAVR have recently been published.[16]

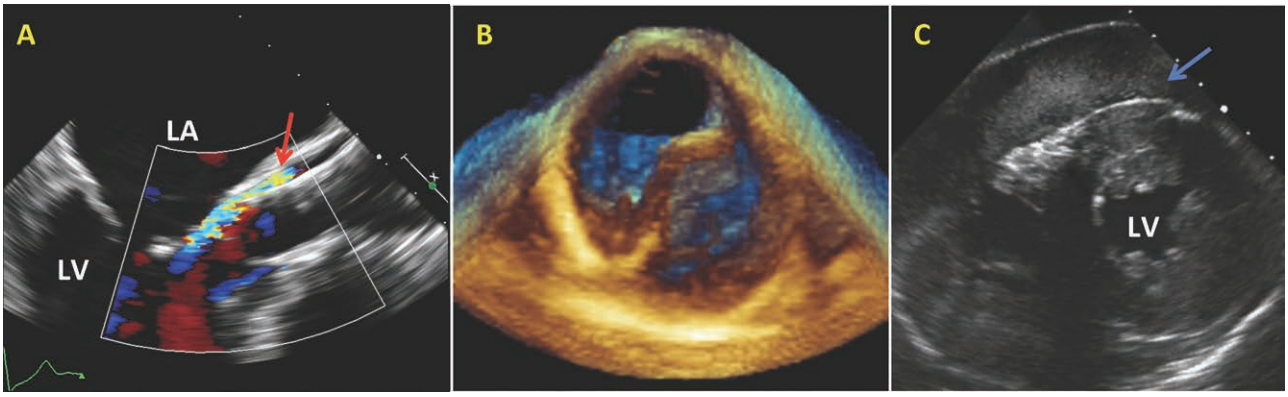

Figure 4. Acute outcomes and complications during transcatheter aortic valve replacement. (A) Mild to moderate paravalvular leak (red arrow). (B) Dissection of the proximal descending aorta. (C) Large hemopericardium (blue arrow) following right ventricular perforation by a pacemaker lead.

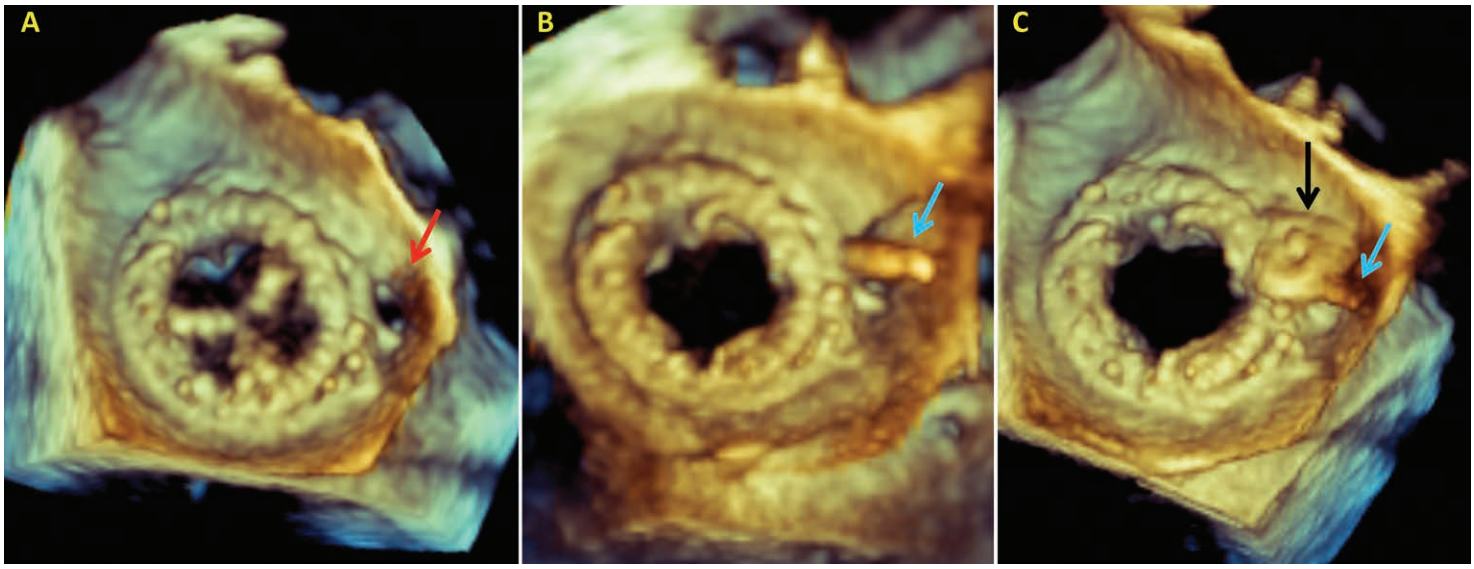

Figure 5. Catheter-based repair of paravalvular mitral regurgitation. (A) A large paravalvular defect is localized along the medial aspect of the prosthesis (red arrow), as viewed from the top of the left atrium during systole. (B) Catheter advancement through the defect during diastole (blue arrow). (C) Repair device (Amplatzer™ ventricular septal defect occluder) already deployed (black arrow) and a catheter (blue arrow) in place to guide placement of a second occluder device.

Transcatheter Repair of Paravalvular Regurgitation

Paravalvular regurgitation may occur after surgical valve replacement, and an incidence of 7% to 17% has been reported for valves in the mitral position.[16] In general, transcatheter repair is more feasible for the mitral valve, although repair of aortic valve defects has been reported. Paravalvular regurgitation is usually caused by infective endocarditis, mitral annular calcification, or traction forces between the prosthetic valve and the native annulus. Percutaneous treatment strategies offer an alternative for patients at high operative risk for redo valve replacement.

Transesophageal echocardiography remains the fundamental imaging modality to assess paravalvular location, severity, and suitability for catheter-based repair (Figure 5). The dehisced area is visualized as an echo dropout area outside the prosthetic valve ring that can be confirmed using color Doppler to demonstrate the paravalvular jet location. Regurgitation severity is assessed with the criteria used for the native valves. Although technically difficult, vena contracta, jet density, systolic pulmonary venous flow reversal, and calculated total regurgitant volume may all be used to assess the severity of paravalvular mitral regurgitation. The proximal isovelocity surface area (PISA) method has not been validated for paravalvular leak evaluation, although a large convergence zone may imply significant regurgitation. However, many factors may limit the accurate quantification of paravalvular regurgitation severity, such as the prosthetic valve ring, native mitral annulus calcification, the irregular shape of the dehiscence, or the presence of multiple jets. Two-dimensional TEE with high spatial resolution may be used to roughly localize the defect (i.e., medial or lateral) and to quickly gauge if it is within the small- to moderate-size range that might be appropriate for catheter-based repair. Using a clock-face terminology, the standard surgical view allows the team to determine defect localization and orientation before, during, and after attempted repair. The aortic valve is typically assigned the 12-o'clock position, the left atrial appendage is typically at the 9- to 10-o'clock position, and the visible defect is assigned another clock face location (e.g., 3 o'clock). This simple nomenclature ensures unambiguous communication between the imaging and intervention members of the treatment team. During the procedure, TEE confirms proper trans-septal puncture location and helps guide catheters to the defect location. Postprocedure TEE confirms the absence of paravalvular leak and possible complications (e.g., prosthetic valve leaflet obstruction by the

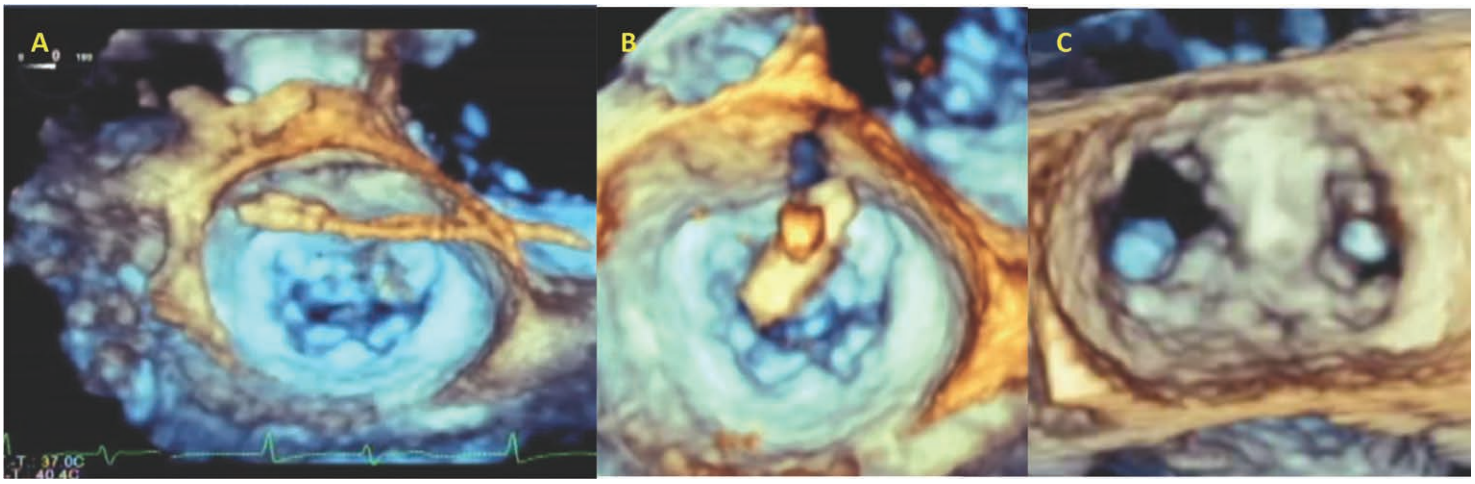

Figure 6. Transcatheter mitral valve repair. (A) Initial delivery of the guide catheter and closure device via trans-septal puncture as viewed from the top of the left atrium (surgical view). (B) Perpendicular alignment of the clip arms relative to line of coaptation. (C) Confirmation of device position with an appropriate double-orifice diastolic leaflet configuration.

device). When used by an experienced echocardiographer, 3D echocardiography with multiplanar reconstruction is a very useful tool to localize and assess the shape and size of the defect. Real-time 3D color is also highly valuable to assess procedural success. As in all structural interventions that rely on precise catheter placement, the 3D "zoom" imaging views allow for real-time visualization of catheters, wires, and devices as they are positioned within the beating heart chambers and as they cross (or fail to cross) the target paravalvular defect.

Percutaneous Mitral Valve Repair

The MitraClip System (Abbott Laboratories. Abbott Park, IL) consists of a two-arm implant with an opening and closing mechanism. Its feasibility and safety has been reported and noninferiority has been shown versus surgery in both functional and degenerative cases of mitral regurgitation in the EVEREST II trial.[18] According to current guidelines, eligible patients must have moderate to severe mitral regurgitation of degenerative or functional etiology that originates along the central leaflet coaptation zone.[16] In the United States, the MitraClip recently received FDA approval for the treatment of degenerative **mitral regurgitation** in patients with prohibitive risk for surgical mitral valve repair.

Two-dimensional TEE is the modality of choice for guiding percutaneous repair procedures. A trans-septal approach has been employed to implant the device using the edge-to-edge repair technique. For easier communication among interventionalists and echocardiographers during the procedure, the Carpentier classification of mitral leaflet anatomy and pathology is routinely employed.[19] Standard views are obtained to image the mitral valve (i.e., midesophageal 4-chamber view, midesophageal 2-chamber view, and midesophageal 3-chamber view). Transesophageal echocardiography is used to examine the precise trans-septal puncture site (3.5 cm to 4 cm above the plane of the mitral annulus), to ensure proper alignment of the catheter within the mitral apparatus, and to place the MitraClip device within the mitral leaflet zone of prolapse or coaptation defect.

Guidelines developed by the European Association of Echocardiography and American Society of Echocardiography propose 2D anatomic eligibility criteria for cases with flail leaflets.[16] Patients with a flail gap—the distance between the tip of the flail leaflet from the opposing normal leaflet—more than 10 mm and a flail width more than 15 mm are not eligible for MitraClip repair. Adequate tissue coaptation length > 2 mm and depth < 1 mm is also required by 2D echocardiography. Color Doppler imaging is used throughout the procedure to assess clip function prior to final release and to define mitral regurgitation severity after final deployment of the MitraClip. At times a second clip must be placed to effect a significant reduction in mitral regurgitation severity, i.e., a reduction from 4+ to 1+ mitral regurgitation. Before the final release of the device, continuous wave Doppler interrogation is used to assess the diastolic gradient across the clipped mitral leaflets. In general, a diastolic gradient less than 5 mm Hg is acceptable.

Recent echocardiography guidelines[5] note that the native mitral valve can be adequately assessed by 3D TEE at the midesophageal 4-chamber view from 0°, 60°, 90°, or 120° imaging perspectives. This modality, particularly the 3D "zoom" function, can be routinely used to visually follow the catheters and wires as they are manipulated within the left atrium and across the mitral leaflets. The 3D TEE-guided MitraClip may be deployed perpendicular to the coaptation line of the two scallops at the site of maximal mitral regurgitation. This determination of "perpendicularity" to the coaptation zone is very difficult, if not impossible, without the use of en-face live 3D imaging. Three-dimensional TEE may also evaluate the position and function of the implant post-procedure (Figure 6).

The final role of the echocardiographer during these procedures is to thoroughly examine for any complications that may not have been recognized. Rarely, a new pericardial effusion is evident (usually a hemopericardium due to chamber perforation), but in general the MitraClip system is largely a venous-access procedure with an excellent safety profile and few complications. Recent advances in 3D TEE have made it feasible to implant these devices safely as a treatment for eligible high-risk patients with significant symptomatic mitral regurgitation.

Conclusion

There is a growing experience using 2D and 3D echocardiography during percutaneous procedures. As new types of valves and devices for valve interventions continue to be developed, intraprocedural echocardiography will play a key role in successful device deployment and postimplantation evaluation. Novel advances in the field of echocardiography may complement

existing technologies, providing the necessary resolution and accuracy for the functional evaluation of newer devices.

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